ANTENNA LABORATORY

Technical Report No. 71

WIDE-BAND CORRUGATED SURFACE ANTENNA

by

MARVIN LEE WAHL

Contract No. AF33(657)-10474
Hitch Element Number 62405484
760 D-Project 6278, Task 6278-01

June 1963

Sponsored by
AERONAUTICAL SYSTEMS DIVISION
WRIGHT-PATTERSON AIR FORCE BASE, OHIO
Project Engineer — James Rippin — ASRNCF-3

ELECTRICAL ENGINEERING DEPARTMENT
ENGINEERING EXPERIMENT STATION
UNIVERSITY OF ILLINOIS
URBANA, ILLINOIS

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Electrical Engineering Department
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Urbana, Illinois

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ACKNOWLEDGEMENT

The author wishes to thank all members of the Antenna Laboratory who gave him help and encouragement. The guidance of his advisor, Professor Raj Mittra, is particularly appreciated. Thanks are also due to Messrs. Richard Peterson and Dennis E. Stropes who performed many of the measurements.

This work was sponsored by the United States Air Force, Wright-Patterson Air Force Base, under Contract number AF33(657)-10474, for which the author is grateful.

1. INTRODUCTION

To the knowledge of the author, no suitable flush-mounted broadband antenna of LP (log-periodic) design has been reported in the literature. Some of the types of designs for flush-mounted antennas which have been attempted by various workers are shown in Figure 1.

Figure 1a is a typical example of a class of structures which is fabricated by starting with a planar LP structure which has a satisfactory but bidirectional pattern, i.e., it radiates symmetrically in both hemispheres above and below the antenna. In order to have the energy radiating in the top half alone, the lower portion is usually blocked off with a series of cavities or even a single cavity. Most of these have been found to exhibit poor performance as broad-band antennas.

Many of the difficulties with the above scheme may be attributed to the reflections from the cavity back used with the planar structure. A procedure shown in Figure 1b, which has been used by Stang[1] to circumvent this, involves the use of a cavity coated with a lossy material. This does not seem to be a very useful solution to the problem if noise and power considerations are taken into account.

Figure 1c shows another configuration that seemingly looks like a dual of the LP dipole antenna. This will not work because the transmission line at the input would be essentially short-circuited by the shunt loops as they got smaller and smaller to satisfy the scaling conditions.

There may be ways of getting around this, but a direct approach would be preferable and it is the purpose of this paper to outline one such approach. Some of the basic principles for LP design will be discussed and applied to synthesize a flush-mounted log-periodic antenna which has been named the Letter-rack antenna. It is an integrated system of slots forming a corrugated surface and a series of loops which will be examined by the theory of coupled modes.

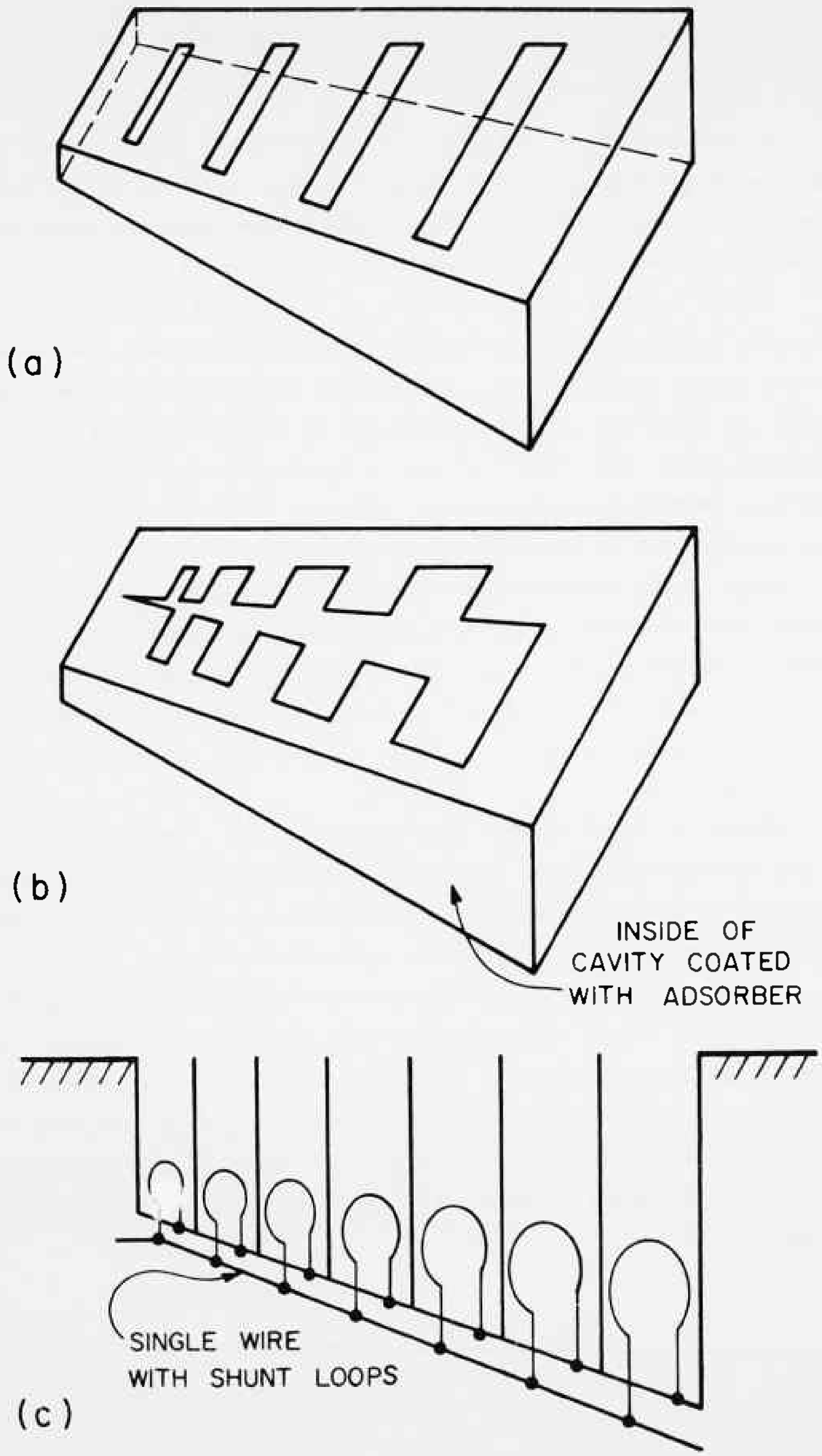

Figure 1. Examples of LP Flush Mounted Antennas Feeds (Not Shown)

2. BASIC CONSIDERATIONS

The purpose here is to outline some of the common design principles of successful LP antennas. So far only backfire types of structures have lent themselves to good LP design. Many of these antennas are built from periodic structures whose propagation constant is complex in certain frequency ranges, i.e., the solution of its characteristic equation is complex valued. The complex solution often referred to as the leaky wave solution assures the decay of fields along the structure away from the feed point. The term leaky wave solution is often used synonymously with a fast wave solution, i.e., one for which the propagation constant associated with one or more of the space harmonics has a real part β_r less than k, where k is the free space wave number. A complex wave does not need to be fast in order for the structure supporting it to radiate effectively. This does not need to be construed to mean that a slow wave would be better than a fast wave. Here the term complex wave will be used to indicate both fast waves and attenuating slow waves.

Although the supporting of a complex wave is necessary, it is not a sufficient condition for a uniform structure to be suitable for LP design. It is suggested that a filter type cutoff frequency region which is often referred to as a "stop-band" is the key to successful LP design. This statement must be interpreted very carefully. Consider, for instance, the two configurations shown in Figure 2. The loaded wave guide acts as a filter and has passbands and stop-bands. In the stop-band, the structure presents a reactive impedance to the source and all the energy launched is reflected back into the generator. In addition, the high attenuation of this mode results in little energy left in the end of the structure. Now consider the two line contra-directional coupler. That also has little end effect in line A because almost all of the energy can be coupled to line B. In contrast to the cutoff filter waveguide, the coupler may be so designed as to have little reflection back into the generator end of line A. It may be misleading to use the term stop-band in connection with this coupler without adequate explanation, as it would suggest a behavior similar to the filter structure.

These examples have interesting analogies to antenna structures. The filter type of configuration resembles a class of antennas which support complex waves, but these waves couple poorly to space. Most of the energy launched on

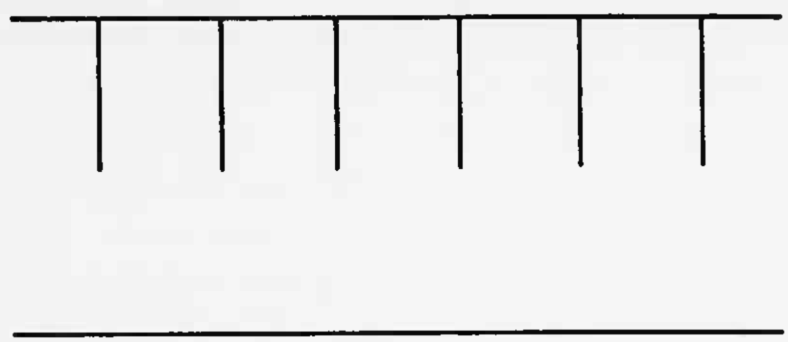

Figure 2a. Periodically Loaded Waveguide

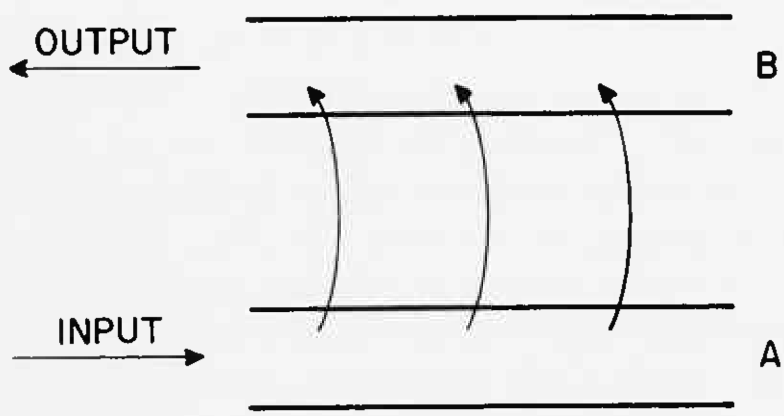

Figure 2b. Two Line Directional Coupler

the surface is reflected back to the feed end and standing waves are set up on the structure. As their impedance and patterns are usually quite frequency dependent, antennas belonging to this class do not lend themselves for wideband design.

The coupler is analogous to a class of antennas whose complex waves radiate effectively into space. Consequently, the standing waves on the structure are small and most of the energy radiates off the desired direction. Line A would be analogous to the guiding structure and line B could be thought of as the space into which the antenna is radiating. This class of antennas has a better broadbanding potential and this is the key to successful LP design.

To summarize, successful LP design is based on the following considerations:

1. The wave should favor backfire radiation, i.e., the main radiation should be toward the feed.

2. The LP structure should support a complex wave region where the wave attenuates. This region is to be preceded by a transmission region where there is little attenuation. The latter condition is particularly important from impedance considerations.

3. The complex wave should couple effectively to space and should reflect little energy back to the generator exciting the guiding structure. However, it is not a necessary criterion that the wave be fast, i.e., the real part of β need not be smaller than k.

It is not implied here that the above conditions are both necessary and sufficient, and a few exceptions also exist, but they are definitely the common characteristic of most of the successful LP antennas built to date.

3. THEORETICAL k-β DIAGRAM FOR CORRUGATED SURFACES

3.1 Calculation of the Theoretical k-β Diagram

One approach to studying the LP antennas is by considering them to be locally periodic along the structure.[2] The period increases with the increasing distance from the apex. Therefore, knowing what is happening to a periodic structure as a function of frequency gives considerable insight into what is happening in a LP version of that structure as a function of distance along it away from the apex. Hence the importance of the Brillouin diagram showing kh as a function of βd where at a given frequency and height in the LP structure the approximate local phase constant βd could be obtained from the Brillouin diagram for the uniform version. Although the corrugated surface shown in Figure 3b will be seen to be unsuitable for use by itself as a broad-band antenna, its k-β diagram will be useful in the coupled mode theory analysis of the Letter-rack antenna.

The corrugated surface has been suggested as a substitute for a reactance surface, and the propagating characteristic of the latter, both unmodulated and modulated, has been reported.[3] However, the approximation of a corrugated surface to being a constant-reactance surface is only good over a narrow band of frequencies. As a little thought will show, the corrugated surface is not a constant-reactance type, but is highly dispersive. The calculating of the k-β diagram has been discussed by Brillouin[4] and Hurd.[5] Hurd's work, which is the latest, has used a function-theoretic approach to obtain the characteristic equation, and he has restricted himself to pure real or surface wave types of solution. An alternate approach for deriving the equation for β will be presented.

The first part of the formulation follows exactly the procedure used by Hurd. In the region above the slots it is assumed that there exists a wave proceeding in the +z direction. This wave will be assumed to have three field components only, E_y, E_z, H_x. The problem is thus a scalar one, and all the field components may be derived from H_x. The appropriate equations are:

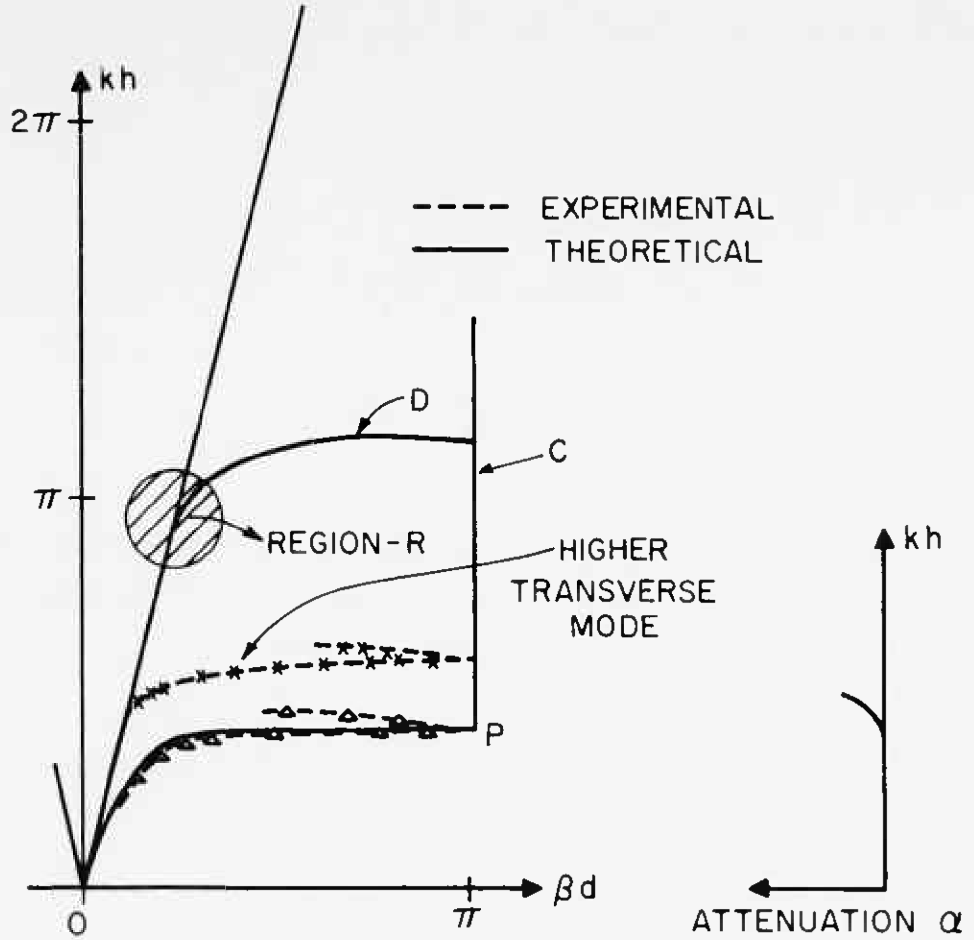

Figure 3a. Theoretical and Experimental k- β Diagram of Uniform Corrugated Surface

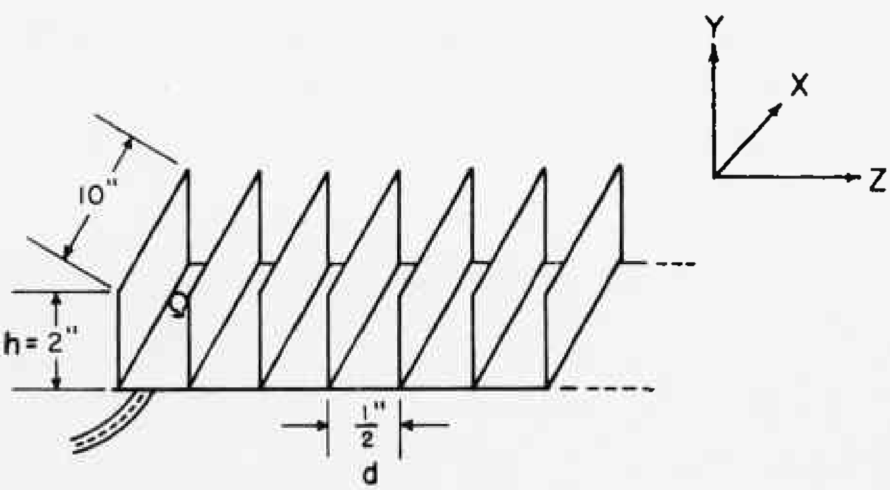

Figure 3b. Uniform Corrugated Surface

$$E_y = -(i/\omega\epsilon)\ \partial/\partial z\ (H_x)$$

$$E_z = (i/\omega\epsilon)\ \partial/\partial_y\ (H_x) \qquad (1)$$

$$(\partial^2/\partial_y^{\ 2} + \partial^2/\partial_z^{\ 2} + k^2)\ H_x = 0$$

On account of the periodic nature of the structure, the field above the slots will not be a simple wave but will be a summation of an infinite number of waves of differing amplitudes and phase constants:

$$H_x = \sum_{n=-\infty}^{\infty} An\ e^{-\alpha_n y - i\beta_n z}$$

$$\alpha_n = (\beta_n^2 - k^2)^{\frac{1}{2}} \qquad (2)$$

$$\beta_n = \beta_o + 2n\pi/d$$

$$(n = 0, \pm 1, \pm 2, \ldots)$$

β_o is the characteristic propagation constant. Let it be assumed that only a TEM mode propagates in the trough region.

The field in the νth slot may be written as

$$H_x^{(\nu)} = \sum_{m=o}^{\infty} \beta_m^{(\nu)} \cos\gamma_m(y+h)\ \cos(m\pi z\nu/d), \qquad y < 0$$

$$(3)$$

$$\gamma_m = \sqrt{k^2 - \frac{m^2\pi^2}{d^2}}$$

To derive the characteristic equation one matches the E_z and H_x field at y=0. Following Hurd, the following determinantal equation may be derived after some algebra:

$$\sum_{n=-\infty}^{\infty} A'_n \left\{ \frac{1}{\alpha_n - \delta_m} + \frac{e^{-2i\gamma mh}}{\alpha_n + \delta_m} \right\} = 0 \tag{4}$$

$$m = 0, 1, \ldots \infty$$

where

$$A'_n = \beta n \, e^{i\beta nd/2} A_n$$

$$\delta_m = i\gamma_m, \quad \delta_o = ik$$

The infinite set of equations has a form similar to the one obtained in the case of a finite bifurcation in a waveguide. This problem has been discussed thoroughly by Mittra.[6] Using the method outlined in that paper for expanding determinants of the type under consideration, one obtains the following expression for the determinantal equation.

$$\Delta + \sum_{m=o}^{\infty} e^{-2i\gamma_m h} \Delta(-\delta_m) + \sum_{n=m+1}^{\infty} \sum_{m=o}^{\infty} e^{-2(\delta_m+\delta_n)h} \Delta(-\delta_m, -\delta_n) + \ldots = 0 \tag{5}$$

The determinant Δ is a double alternant (for details see Muir[7]) and may be expressed as a ratio of products involving α_n and δ_m.

The desired determinantal equation is

$$2kh = \pi - 2\sin^{-1}(k/\beta_o) + \frac{kd}{2\pi}\ \ell n\ 2 + \tau(\psi_1, kd/\pi)$$
$$-\tau(\psi_2, \frac{kd}{2\pi}) - \tau(\psi_3, \frac{kd}{2\pi}) \qquad (6)$$

where

$$\tau(u,v) = \sum_{n=1}^{\infty} \sin^{-1}(u_n - \frac{v}{n})$$

and

$$\psi_{1n} = \frac{kd}{n\pi}\ , \quad \psi_{2n} = \frac{k}{\beta_n}\ , \quad \psi_{3n} = \frac{k}{|\beta_{-n}|}$$

The k-β diagram was calculated for the corrugated surface structure using Equation (6) and the results are shown in Figure 3a. Note particularly that above the turnover point P there exists a pair of complex conjugate solutions with the β equal to π. No other solutions were found in this range, although a numerical search for a possible root was made on a digital computer on a very thorough basis. A typical higher order solution is shown by curve D in Figure 3a. A thorough search was also made for a solution of the equation in the region R in order to find a continuation of the curve D. No physically admissible solution has been found so far, at least. This problem is currently under further investigation by the Antenna Laboratory at the University of Illinois. In effect then, except for the solution designated by C in Figure 3a, no complex solution has been found to date even after a fairly thorough search with the computer.

3.2 Interpretation of Theoretical k-β Diagram

The interpretation of the k-β diagram for the corrugated structure considered above is fairly simple. The solid curves in Figure 3a represent surface wave type of solutions. The only complex solutions found are represented by the vertical line at $\beta = \pi$. It may be shown that this solution has the same

character as the filter type attenuated mode in a closed structure. Theoretically, for an infinite structure, there is no radiation from the fields described by this mode solution. Lack of other complex solutions of the determinantal equation must not be so interpreted as to mean that the structure has no radiation. The continuous spectrum of spatial frequencies is always present when one is considering a source problem. In this particular case, a convenient alternate representation for what may be a majority portion of the fields in terms of other complex solutions was unable to be found. In any event, this structure is not expected to produce primarily backfire pattern, one of the criteria which was set forth as desirable. Complex solutions with a leading phase constant β, and which produce fields that couple fairly effectively to space is what we are seeking. A possible modification which will make it possible to realize such a characteristic is discussed in the following section.

3.3 Modification for Realizing a Backfire Condition

Consider the modification that results in the k- β diagram of the corrugated structure when it is coupled to another system which has its k- β diagram shown by the line B in Figure 4. If these two systems couple effectively near I, complex solutions will result (for details on coupled mode theory see Louisell[8]) in the neighborhood of the point of intersection of the unperturbed solutions associated with the two systems. Since the location of I is in the leading phase region, backfire patterns will be expected. For lower frequencies when the two unperturbed solutions are far apart, modification of the solutions due to coupling will be small and two different mode solutions will be expected. It is not possible to say without solving the source problem what the relative amplitude of excitations of these two mode amplitudes will be. One would expect though that there will be regions where the solution A will be predominant and some others where the influence of B will be larger. Where A dominates, the patterns will be primarly endfire whereas backfire radiation will be expected in regions where the composite solution is closer to B. One expects the solution B to dominate in the vicinity of the point I (see Figure 4) for waves traveling in the positive direction. A straightforward system which will produce a k- β characteristic of the type B is shown in Figure 5. The picture shows a transmission line loaded periodically with series loops which alternate in their sense of winding. Assuming the current flows along the loops at

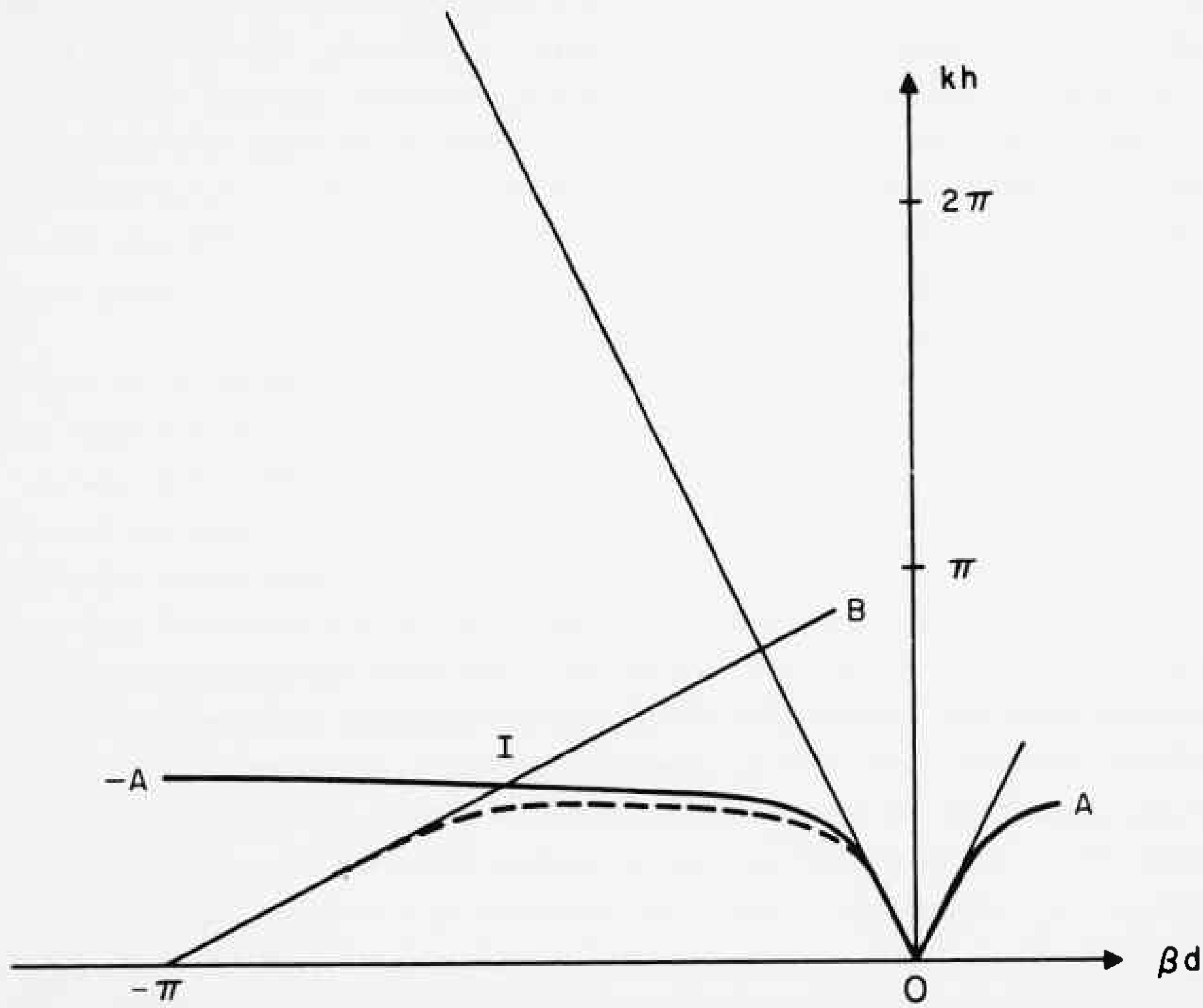

Figure 4. k- β Diagram Showing Coupling of Modes

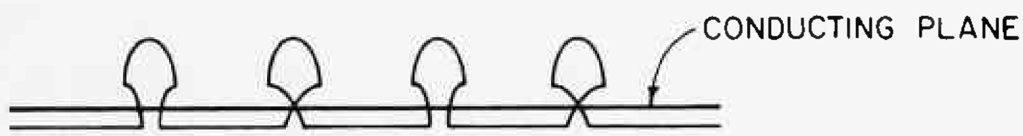

Figure 5. Transmission Line Periodically Loaded with Alternately Transposed Loops

velocity of light one expects the slope of the curve B to be smaller than 1 and the limiting value of β as $k \to 0$ to be π. This is the type of characteristic we have been looking for. A coupled system is shown in Figure 6. Next are the experimental measurements on the corrugated surface and the coupled system and finally the wide-band corrugated surface antenna.

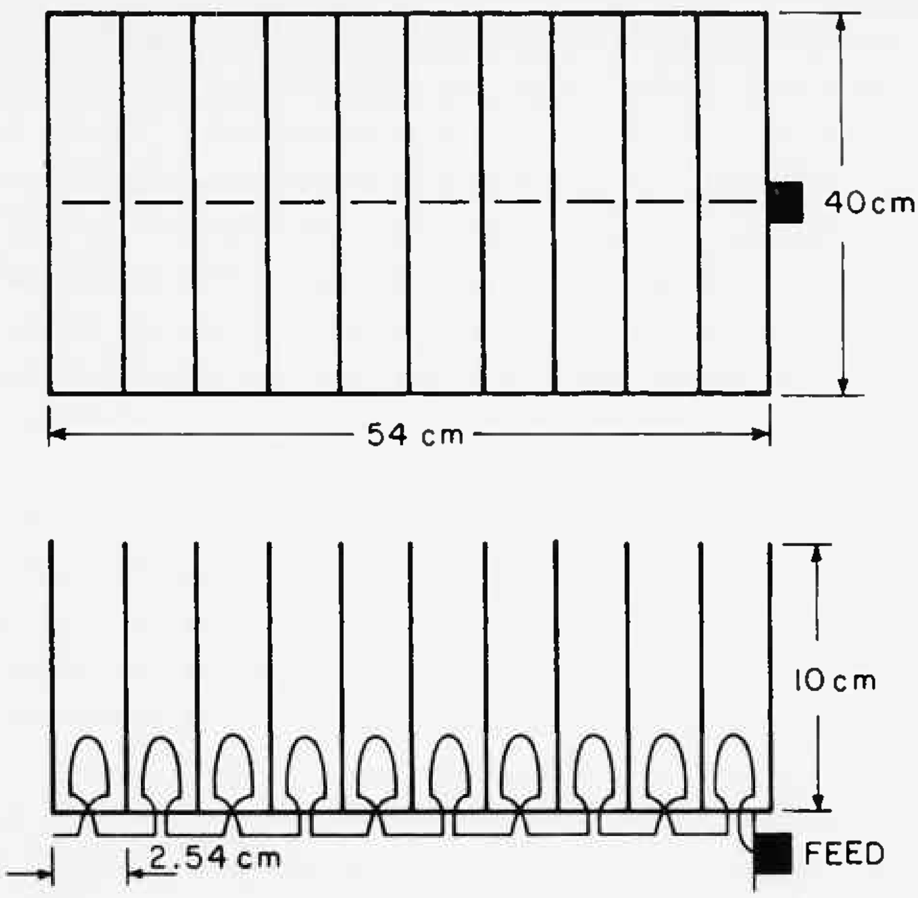

Figure 6. Uniform Letter-Rack Antenna
21 Cavaties
Slot Depth $\lambda/4$ at 750 MC

4. EXPERIMENTAL RESULTS

4.1 The Corrugated Surface

The uniform corrugated surface was made by stacking 2" x 10" aluminum plates. The bottom of the troughs was also aluminum. A sketch of this structure is shown in Figure 3 along with other details. After considering various possible feeds, such as a horn or single wire exciter, it was decided to use a single loop feed at one end of the structure. This feed showed fairly efficient coupling to the structure when it was placed near the bottom of the first trough and yet had little direct contribution to the far field.

An automatic plotter was used to plot the near field amplitude of the H_x-field as a function of distance along the structure. The probe and the antenna were placed in an anechoic chamber.

In the frequency range where there is little attenuation of the wave supported by the structure, it is convenient to measure β by putting a large shorting plane on the end of the structure and setting up standing waves on the surface. The guide half-wavelength ($\lambda g/2$) can be determined by measuring the distance between two minimas. The measured values of $\beta d=2\pi d/\lambda g$ are plotted in Figure 3 as a function of kh.

At low frequencies the experimental points are quite close to the theoretical curve and the attenuation of the wave is negligible. Only near the turnover point P does the attenuation become noticeable.

Above the turnover point the experimental curve tends to turn back toward smaller values of β instead of following along the line $\beta = \pi$ which was calculated theoretically. One possible explanation for this is the following.

In the frequency range above the turnover point, the fields due to a given source must be described by including the spatial frequencies which have a continuous spectrum. The small frequency range above the turnover point is a sort of transition region between the surface wave mode and continuous spectrum type of behavior. In this region the values can be approximately tracked up to a certain frequency beyond which no meaningful measurements could be made until the next mode is reached. The next mode, corresponding to a cosine distribution in the transverse direction, has surface wave propagation until its turnover point is reached.

The possibility of the existence of another complex solution of the characteristic equation which will correspond to the experimentally measured point is currently being investigated at the Antenna Laboratory of the University of Illinois.[9] However this question still remains open.

So far, the experimental measurements and experimental far field patterns have not convincingly demonstrated such a solution.

4.2 Uniform Version of the Corrugated Surface with Multiple Loop Feed

A uniform version of the corrugated surface antenna, i.e., one with $\tau = 1$, was built and studied in order to gain an insight into the behavior of its LP counterpart.

The uniform version was constructed by bolting aluminum plates with right angle bends to a sheet of aluminum. Holes drilled in the center of the bottom of each slot allowed the feed cable to pass in and out of each slot. The loops were formed by the feed cable held in place by polyfoam spacers and every other loop was wound in the opposite direction. The tops of the plates were spaced by pieces of plexiglass. The dimensions of this model are shown in Figure 6.

A Rohde and Schwarz diagraph was used to measure near field phase and amplitude of the H_x field over each cell. Again, the field probe and the antenna were placed in an anechoic chamber.

The experimental results in Figure 7 show $\frac{kd}{2\pi}$ versus normalized phase shift per cell $\frac{\beta d}{2\pi}$. In the region kd below .035, the points indicate a wave traveling down the feed wire, mode B, with slowness of about 13.5, whereas the slowness expected if the current were assumed to be traveling along the wire with free space velocity would be 11. This could be explained by noting an additional loading effect on the feed line due to its close proximity to the corrugated surface. The coupling at point I has been discussed previously. Far field measurements at these frequencies show a backfire type of pattern, as shown in Figure 8.

At higher values of kd the experimental points follow the curve +A. Corresponding far fields measurements show an endfire type of pattern.

A higher order mode appears to dominate at even higher kd values giving a far field pattern which is split or double lobed in the aperture plane (see Figure 8).

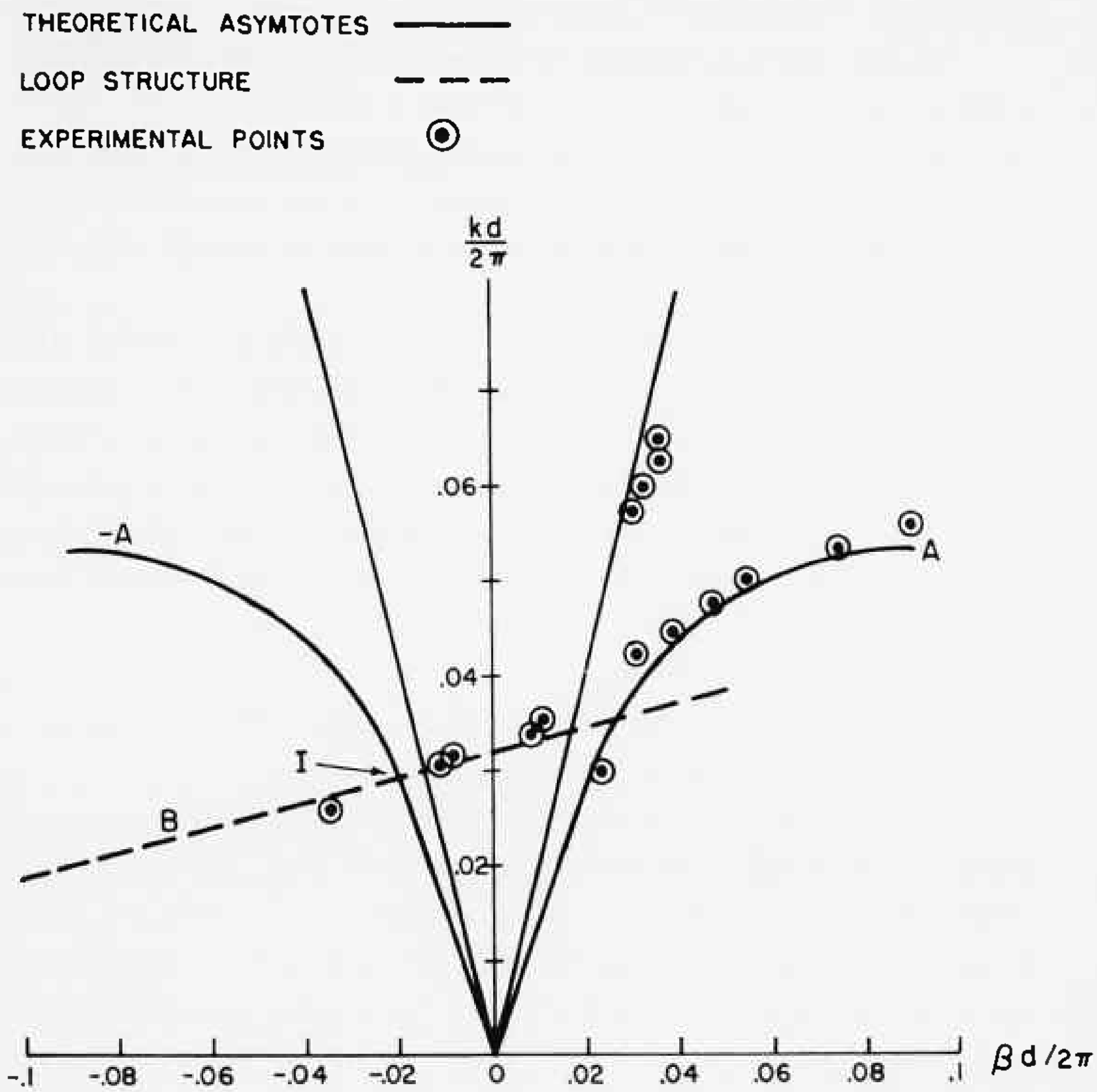

Figure 7. K - β Diagram of Uniform Corrugated Surface with Multiple Loop Feed

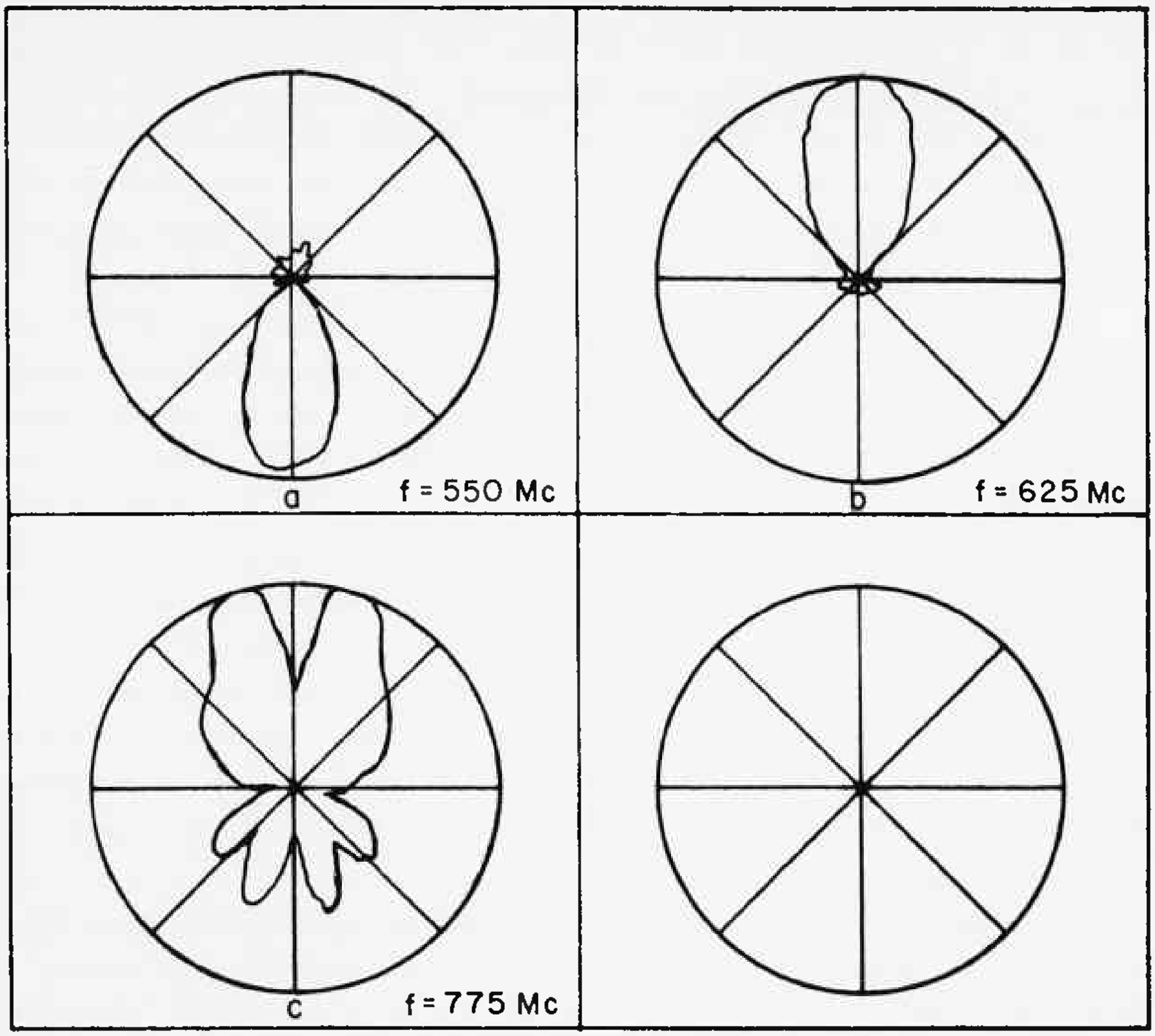

Figure 8. Three Patterns of the Uniform Letter-Rack Antenna

From this information, it can be predicted that the LP version should work satisfactorily if radiation due to mode +A and higher order modes is small and if the effective radiation comes from the coupled curves B and -A.

4.3 The Wide-Band Corrugated Surface Antenna

The LP corrugated surface with multiple feed was constructed in the same manner as the uniform version except all dimensions were scaled by a factor τ from cell to cell. A sketch of this structure is shown in Figure 9.

A typical near field amplitude plot of the transverse H-field as a function of distance along the structure is shown in Figure 10. Note that the wave is fairly well bound at the input end of the antenna but becomes more and more loosely attached to the surface as it approaches the active region where the field amplitude reaches a maximum. The H_x field decays very rapidly beyond this point, and there is no significant energy left at the end of the structure. The near field phase measurements show a leading phase distribution in regions where the amplitude is significant. This indicates mode B is predominant in most of the regions of interest, and hence the LP structure produces a predominately backfire pattern. The near field measurements also scale fairly well with frequency indicating a broadband performance. The H-field behavior measured on this structure shows a strong resemblance to the current distribution at the base of the dipoles in the log-periodic dipole array, as reported by Carrel.[10]

A larger model of the wide-band corrugated surface antenna to fit into a 30in. Circular aperture was built for impedance measurements. The spacing away from ground or feedline from loop to loop was left variable. The impedances of this antenna over its design range are shown in Figure 11. The points shown were taken with the feedline very close to the bottom plate of the antenna which is grounded.

A predominately backfire type of pattern over a wide range of frequencies is exhibited by the far-field measurements on the wide-band corrugated surface, the Letter-rack antenna.[11] These are shown in Figure 12. Note that low frequency performance extends down to 500 mcs., whereas the frequency at which the last slot becomes a quarter wavelength is above 850 mcs. This may be explained by going back to the coupled mode approach discussed earlier. Referring back to Figure 4, if there is a strong interaction between the corrugated surface and the loop structure, i.e., between curves -A and B, the resulting curve will

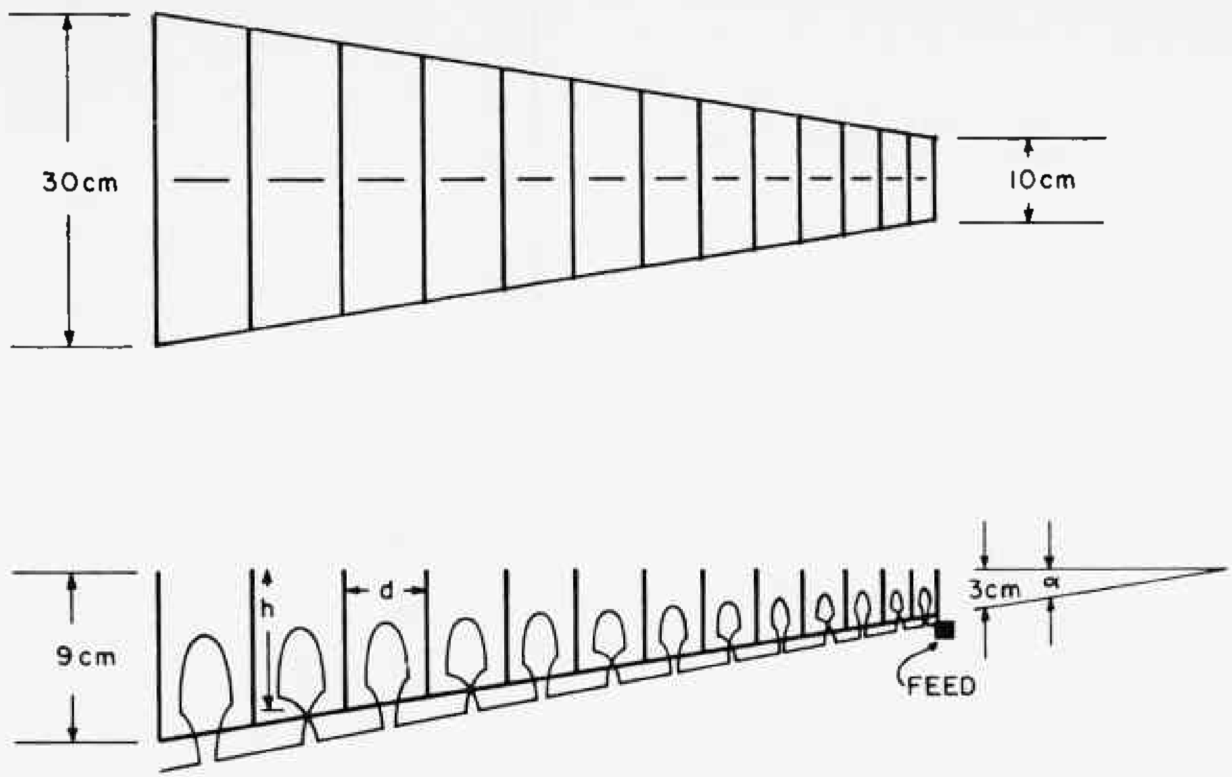

Figure 9. The LP Letter-Rack Antenna

Last Slot is $\lambda/4$ at 850 MC
τ = .97
h/d = 4.5/1
37 Elements
$\alpha = 9^{0}$

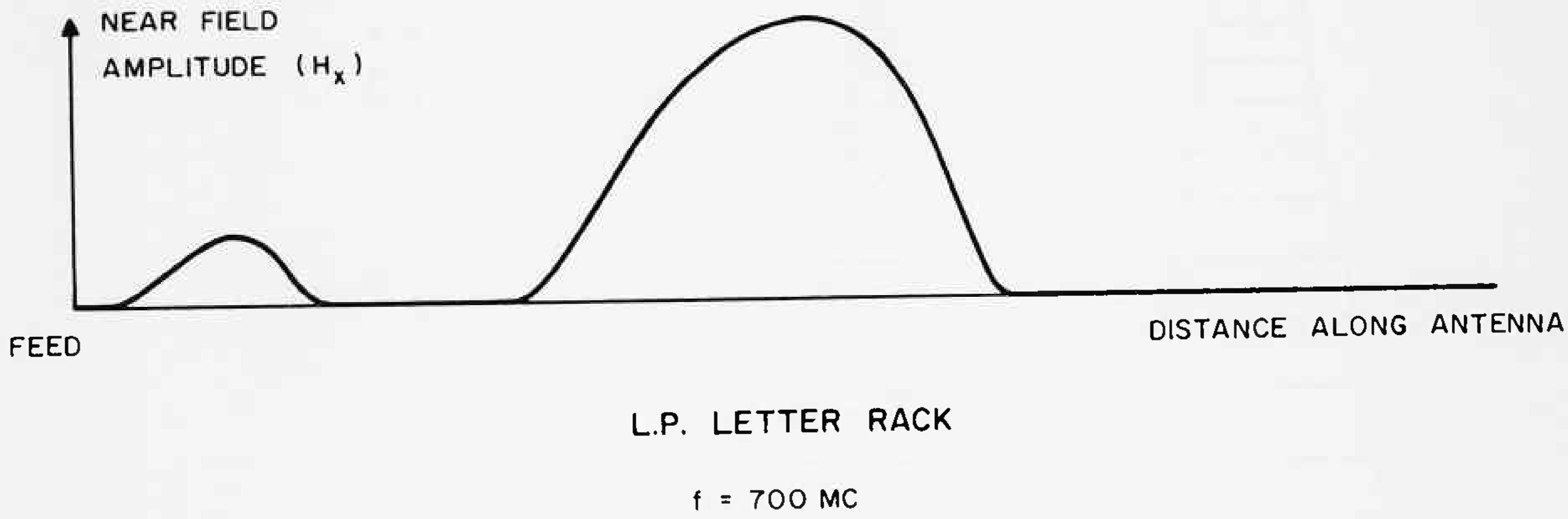

Figure 10. Typical Near Field Amplitude of the Log-Periodic Letter-Rack Antenna

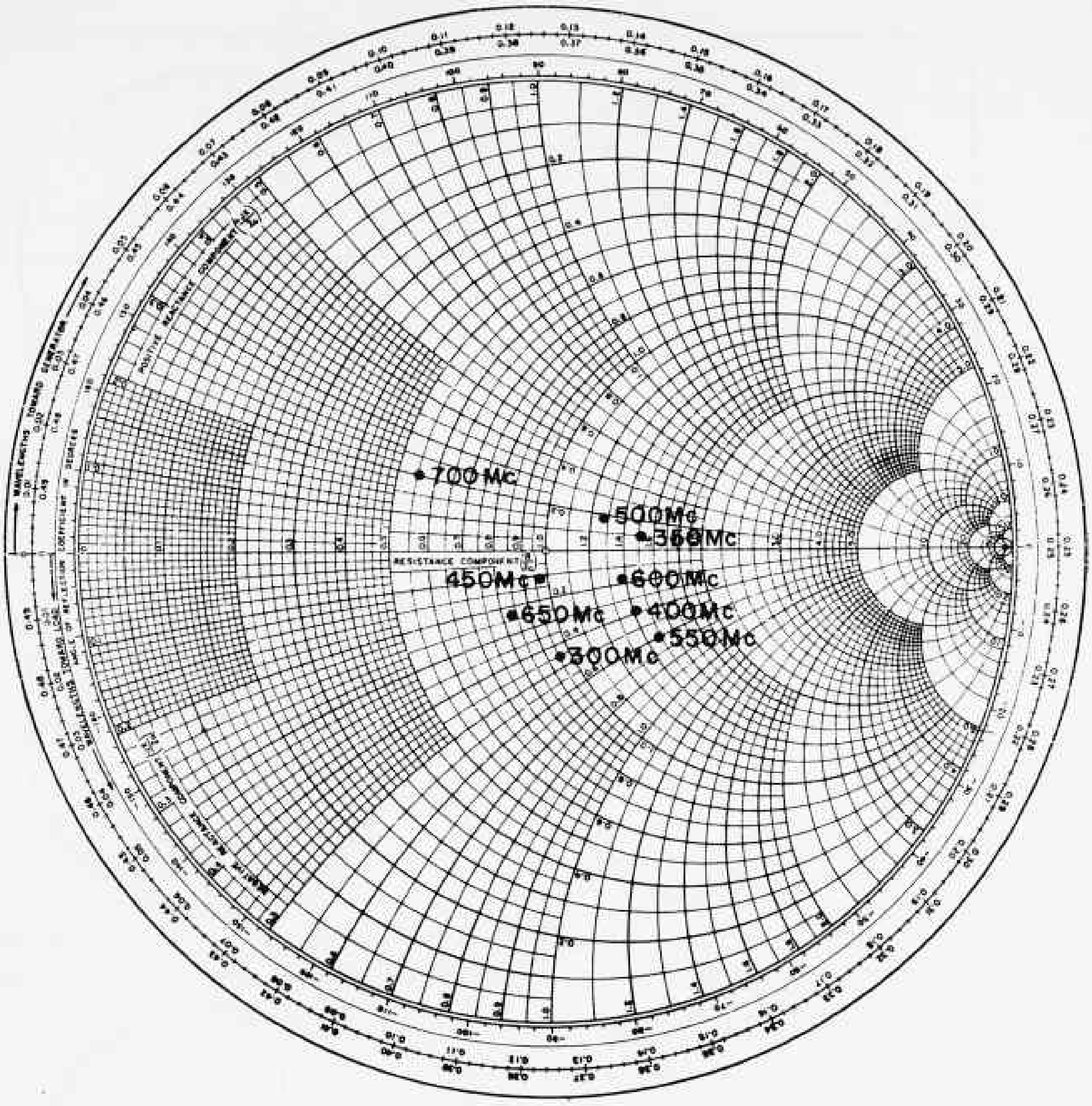

Figure 11. Impedance of a Wide-band Corrugated Surface Antenna

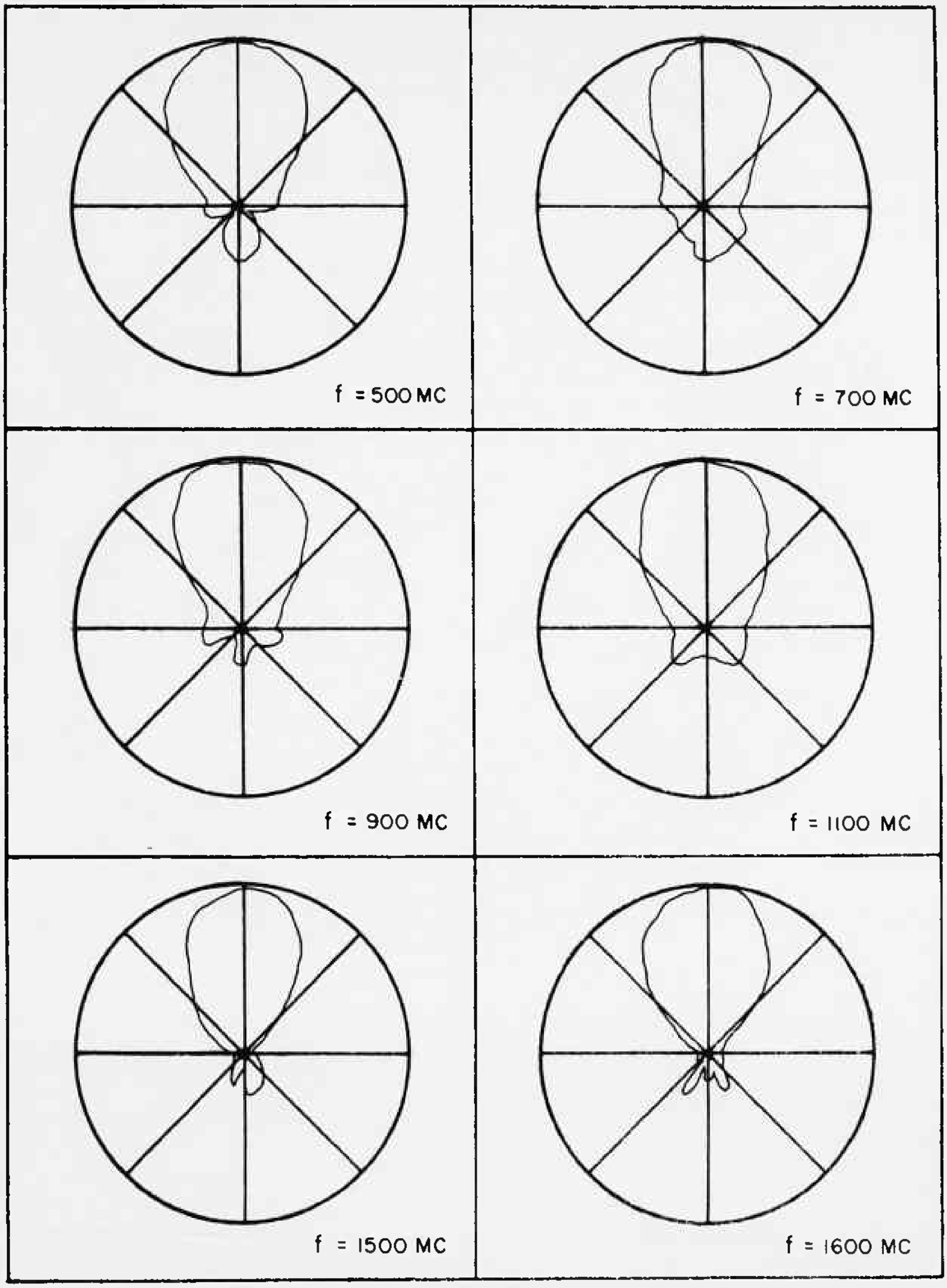

Figure 12. Far Field Patterns of the Log-Periodic Letter-Rack Antenna

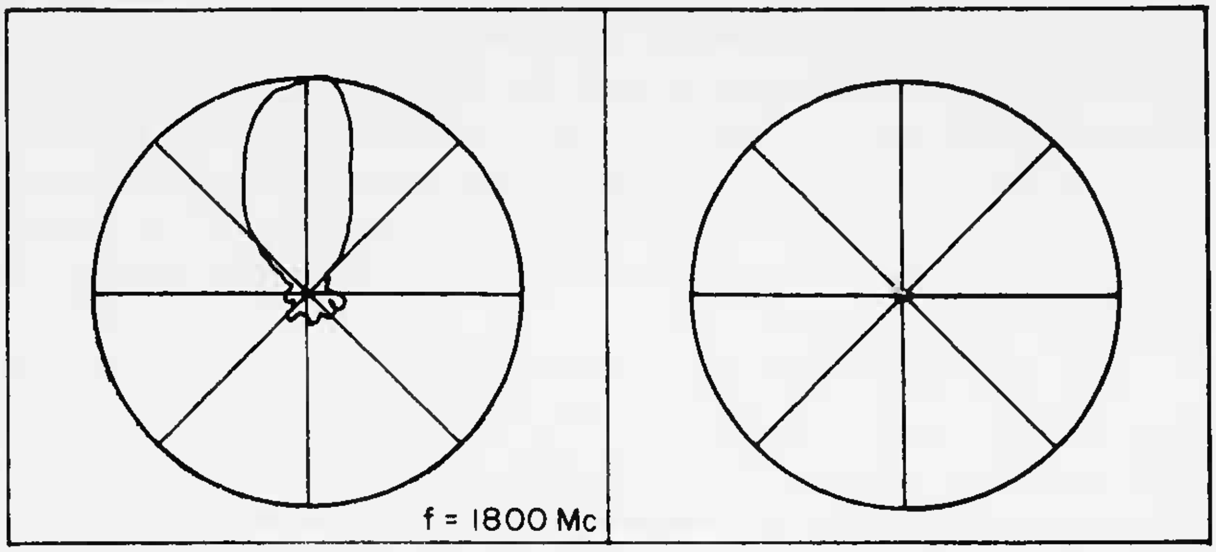

Figure 12a (cont'd). A Far-Field Pattern of the Log-Periodic Letter-Rack Antenna

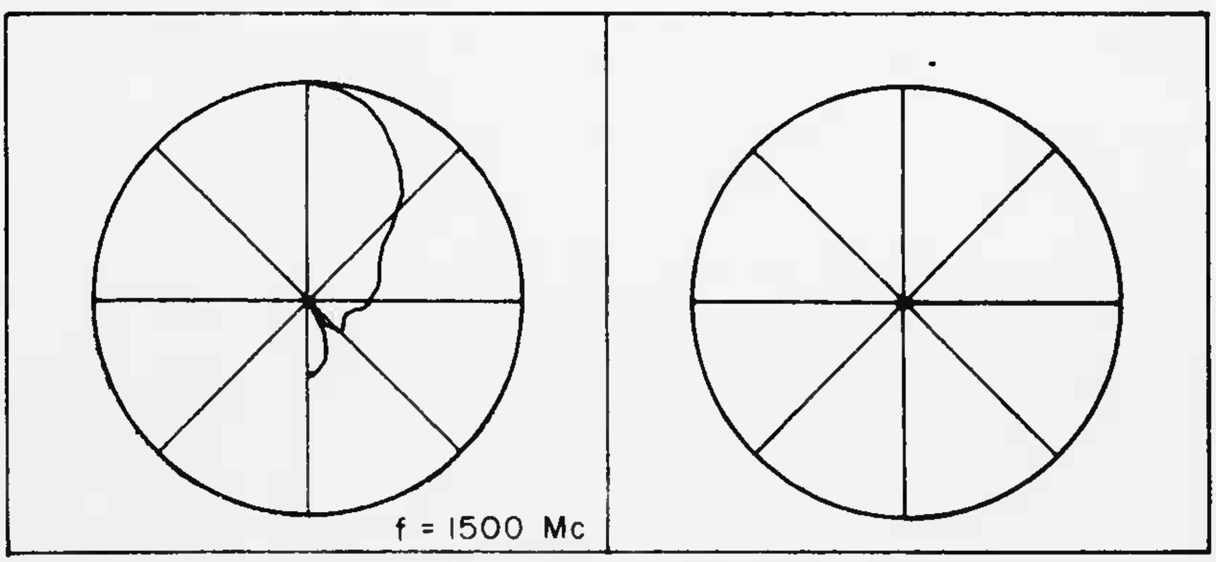

Figure 12b. Typical Far-field Pattern (E Plane) of LP Letter-Rack Antenna

have a turnover point considerably lower than the frequency corresponding to the point I. As a consequence of this, the frequency at which the slots start attenuating the wave will lower the point I. Also note that the point I could be substantially lower than thc turnover point of curve A depending on the slope of curve B. Hence the usable low frequency limit of the antenna will be considerably lower than that predicted by the quarter wave resonance frequency of the largest slot.

The above behavior is tied up with the strength of interaction between the corrugated surface and the feed structure and the predominance of mode B with desired attenuation. If the loops are made very small, the performance of the antenna deteriorates considerably. The bandwidth becomes narrower, the front-to-back ratio becomes smaller, and the standing wave ratio at the input increases as a result. These can be attributed to the presence of the undesired mode, i.e., mode +A, in the radiation region, weak coupling between -A and B resulting in lower attenuation along the structure for the complex wave and hence larger end effect, and poor conversion of the transmission wave into the radiating wave and hence larger reflected wave toward the feed. Therefore, it is quite important to design the antenna in such a manner as to insure coupling between the corrugated surface and the loop structure.

5. CONCLUSION

It was shown why the simple corrugated surface is not suitable for broadband design without some basic changes. A composite system consisting of a series of alternately transposed loops and the corrugated surface was constructed such that the two periodic systems couple strongly to each other. Then a tapered version, a wide-band flush-mounted antenna, also called the Letter-rack antenna,[11] was designed from the previously gained knowledge. The behavior of the coupled system was studied on the basis of coupled mode theory. The significance of the k- β diagram to the LP antenna design was also outlined. The purpose of this project was not to design a particular piece of hardware for a particular job, but to outline certain principles which might help in understanding the behavior of a class of LP antennas and to design some new ones on the basis of this understanding. Another successful antenna, a series-loaded folded dipole structure shown in Figure 13, has been built following these principles.

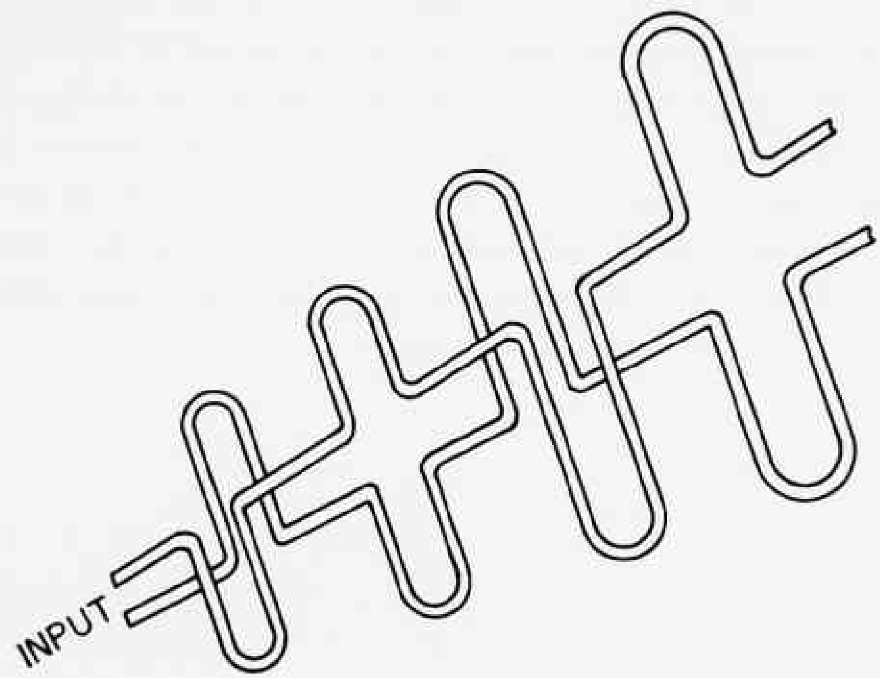

Figure 13. Log-Periodic Folded Dipole Array

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Scottsdale, Arizona

Philco Corporation
Antenna Section
3875 Fabian Way
Palo Alto, California

Space Technology Laboratory
Attn: Research Library
P. O. Box 95100
Los Angeles 45, California

All Products Company
Attn: James Buzbee
Mineral Wells, Texas

Avco Corporation
Electronic and Ordnance Division
Attn: Technical Library
Cincinnati 41, Ohio

Bendix Corporation
Research Labs Division
Attn: G. M. Peace
Southfield (Detroit), Michigan

Douglas Aircraft Co., Inc.
Attn: MSSD Technical Library
(Antenna Section)
3000 Ocean Park Blvd.
Santa Monica, California

Emerson and Cuming, Inc.
Attn: E. J. Luoma
869 Washington Street
Canton, Massachusetts

Radioplane Company
Attn: Librarian (M/F Aerospace Lab)
1515 Rancho Conelo Blvd.
Newbury Park, California

Hughes Aircraft Company
Attn: Antenna Section
Fullerton, California

Vincent De Santi, Chief
Exchange Section
Document Control Department
Scientific and Technical Information
Facility
P. O. Box 5700
Bethesda, Maryland

Canoga Electronics Corporation
Attn: Advanced Programs Department
15330 Oxnard Street
Van Nuys, California

North American Aviation, Inc.
Autonetics Division
Advanced Engineering Laboratory
Attn: System Technology Department
La Palmas Road
Anaheim, California